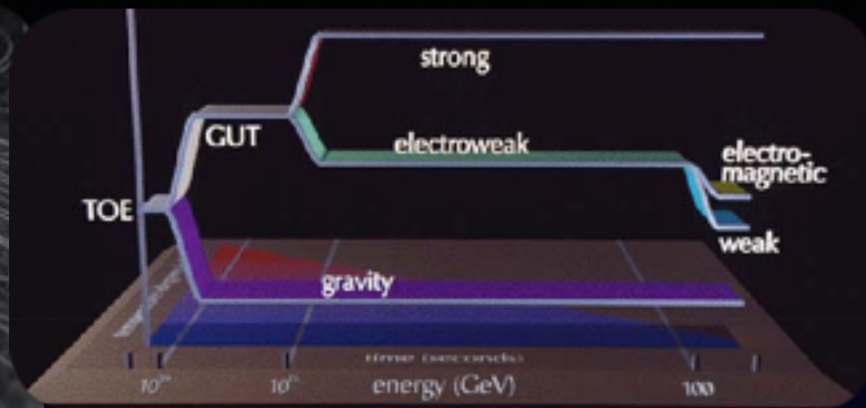
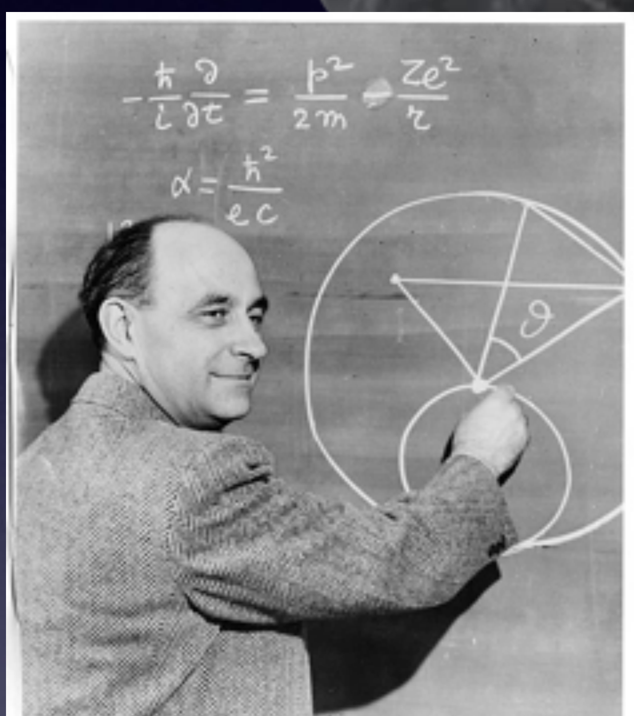
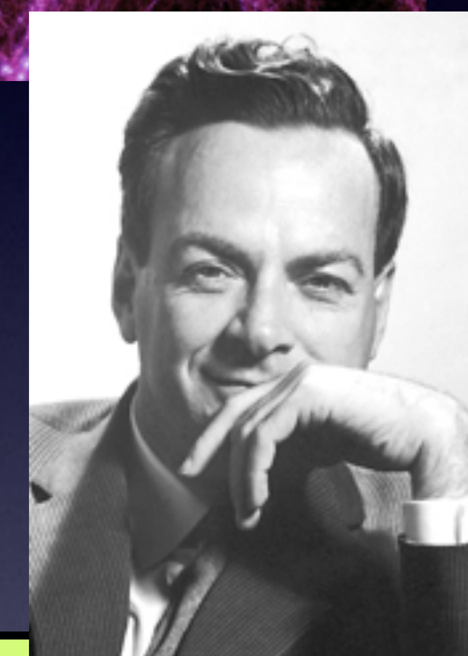
Vectorial Dark Matter in the Universe







« Never underestimate the joy people derive from hearing something they already know.»
E. Fermi

Yann Mambrini,

University of Paris-Saclay

in collaboration with

Soo-Min Choi, Hyun Min Lee (Chung-Ang University, Seoul),

Hitoshi Murayama, Y. Hochberg, E. Kuflik, Mathias Pierre

« It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.»
R. Feynman

ERC Higgs@LHC

Joint workshop of the France Korea Particle Physics meeting, Strasbourg, May 10th 2017

A la mémoire de Pierre Binetruy

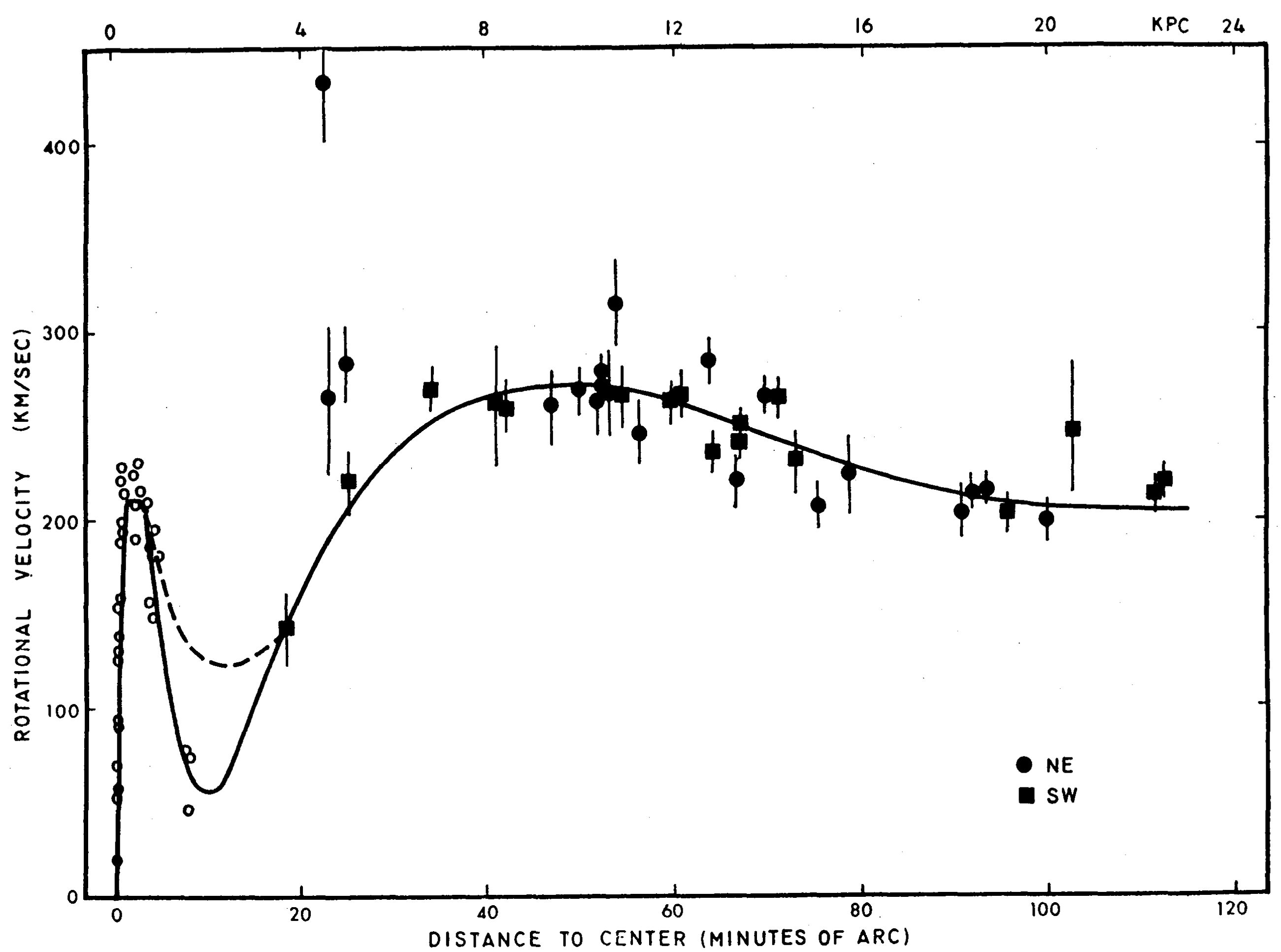
A tribute to Vera Rubin

Vera Rubin
(1928-2016)

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21



Andromeda, M31

which will establish the amount of neutral hydrogen. For the present, we prefer to adopt as the mass of M31 that mass contained within the outermost observed point; extrapolation beyond that distance is clearly a matter of taste.

The first DM paper

Henri Poincaré

Contrarily to the common belief, the first time the word « dark matter » is proposed in a scientific paper is not Oort in 1932 but Poincaré in 1906. Indeed, Lord Kelvin in 1904 had the genius to apply the kinetic theory of gas recently elaborated, to the galactic structures in his Baltimore lecture (*molecular dynamics and the wave theory of light*). Poincaré was impressed by this idea and computed the amount of stars in the Milky way necessary to explain the velocity of our sun one observes nowadays.

THE MILKY WAY AND THE THEORY OF GASES.*

H. POINCARÉ.†

equation of living forces. We thus find that this velocity is proportional to the radius of the sphere and to the square root of its density. If the mass of this sphere were that of the Sun and its radius that of the terrestrial orbit, it is easy to see that this velocity would be that of the Earth in its orbit. In the case that we have supposed, the mass of the Sun should be distributed in a sphere with a radius one million times larger, this radius being the distance of the nearest stars; the density is then 10^{18} times less; now the velocities are of the same order, hence it must be that the radius is 10^9 times greater, that is one thousand times the distance of the nearest stars, which would make about one thousand millions of stars in the Milky Way.

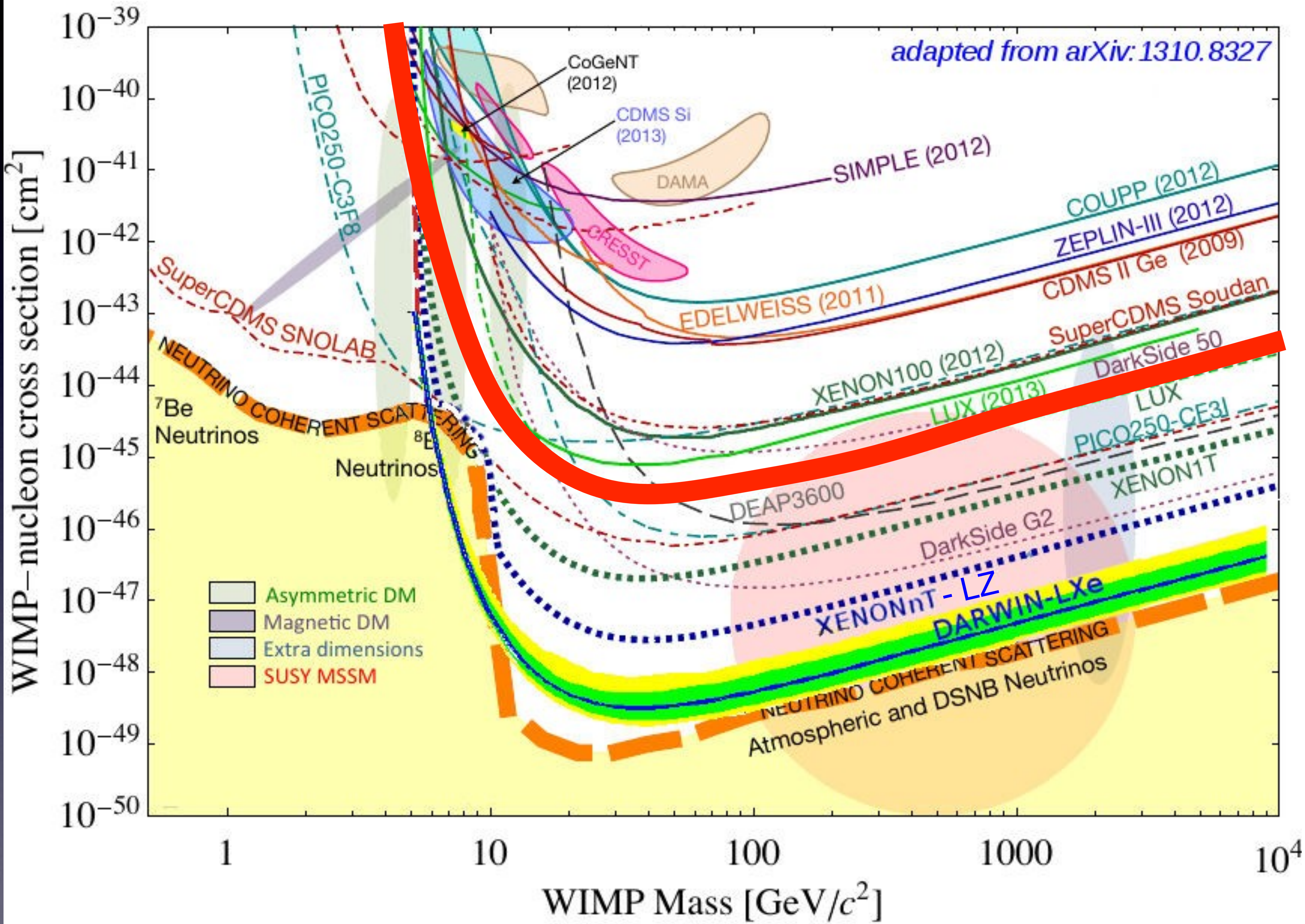
ence might long remain unknown? Very well then, that which Lord Kelvin's method would give us would be the total number of stars including the dark ones; since his number is comparable to that which the telescope gives, then there is no dark matter, or at least not so much as there is of shining matter.

Where are we now?

1

The direct detection race

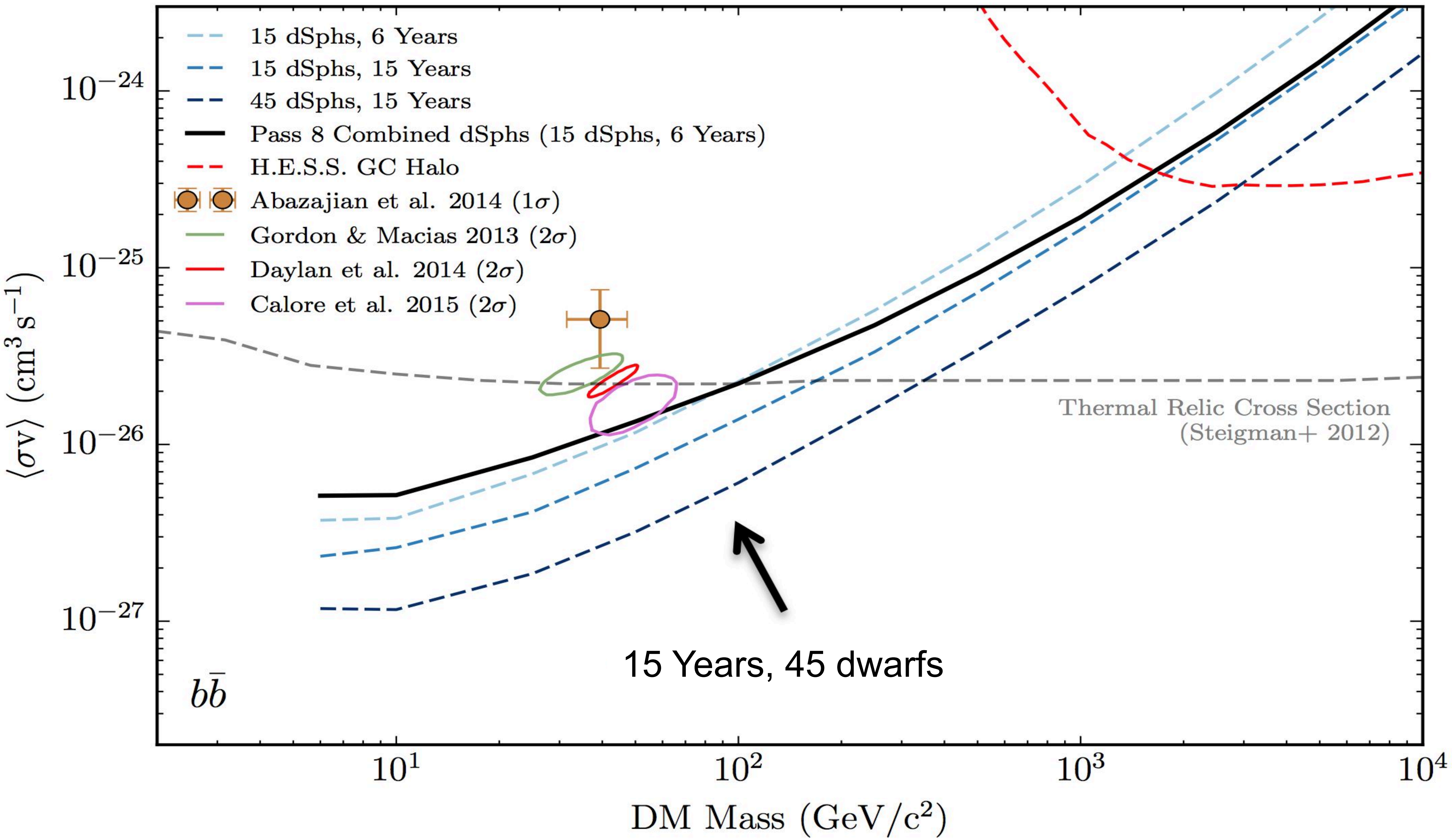
Perspectives



2

The indirect detection status

DM limit improvement estimate in 15 years with the composite likelihood approach (2008- 2023)



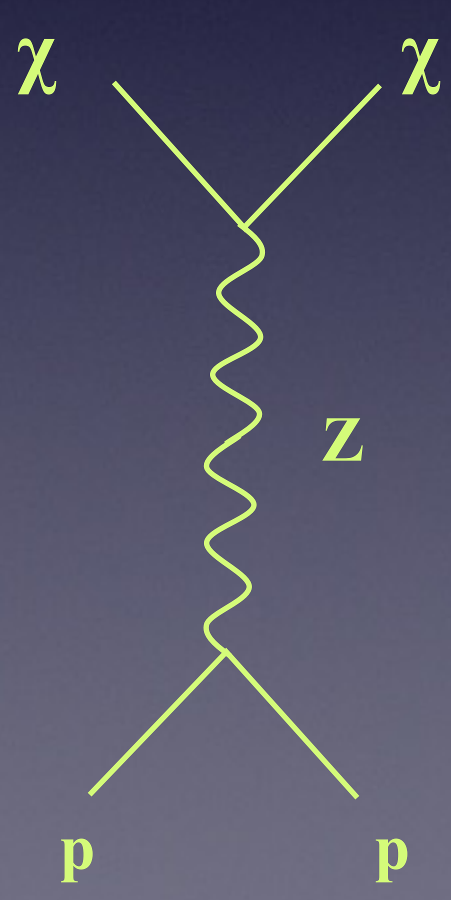
E. Charles et.al, Phy Rep. 636 2016, arXiv:1605.02016

Latest result by FERMI in May: nothing

Conclusion

The **non-observation** of any signal at direct and indirect detection experiments constrains the interaction cross section DM-SM to values below $\sigma < 10^{-46}\ \text{cm}^2 \sim 10^{-18}\ \text{GeV}^{-2}$

What do we expect for a WIMP*:

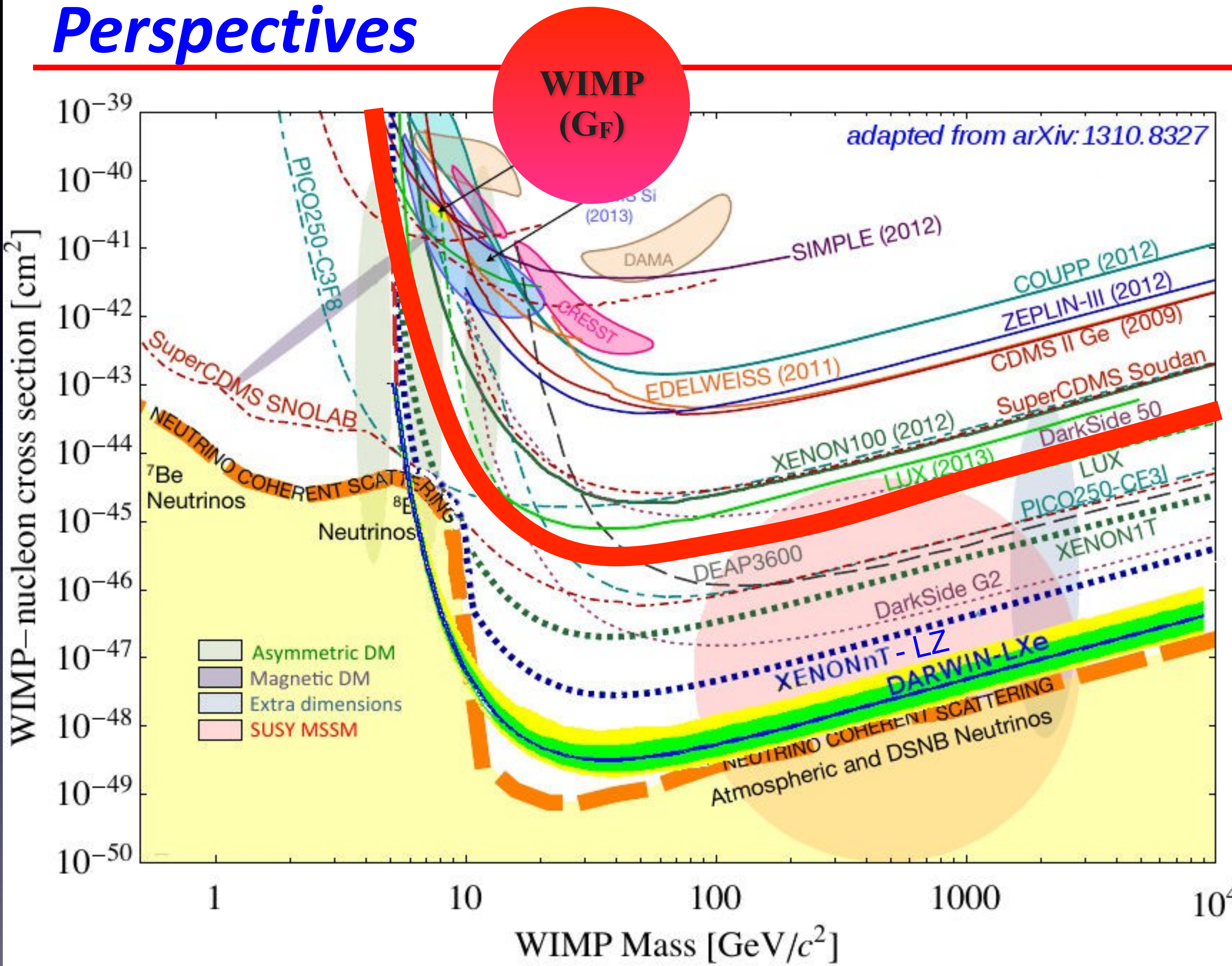


$$\sigma_{EW}(\chi\, p \to \chi\, p) \simeq G_F^2 m_\chi^2$$

$$\simeq \frac{g_2^2}{M_Z^4} m_\chi^2 \simeq 10^{-9} \left(\frac{m_\chi}{1\ \text{GeV}}\right)^2$$

*Not valid if one exchanges the Higgs or a Z’

Perspectives



« The waning of the WIMP? Review of Models, Searches and Constraints »

G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M.,
M. Pierre, S. Profumo and F. Queiroz;
arXiv:1703.07364

Why are we so attached to WIMP-like particle?

The WIMP miracle !

The Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

$$\Omega_A h^2 \simeq \frac{0.17}{\frac{\langle \sigma v \rangle}{(1.2 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})}}$$

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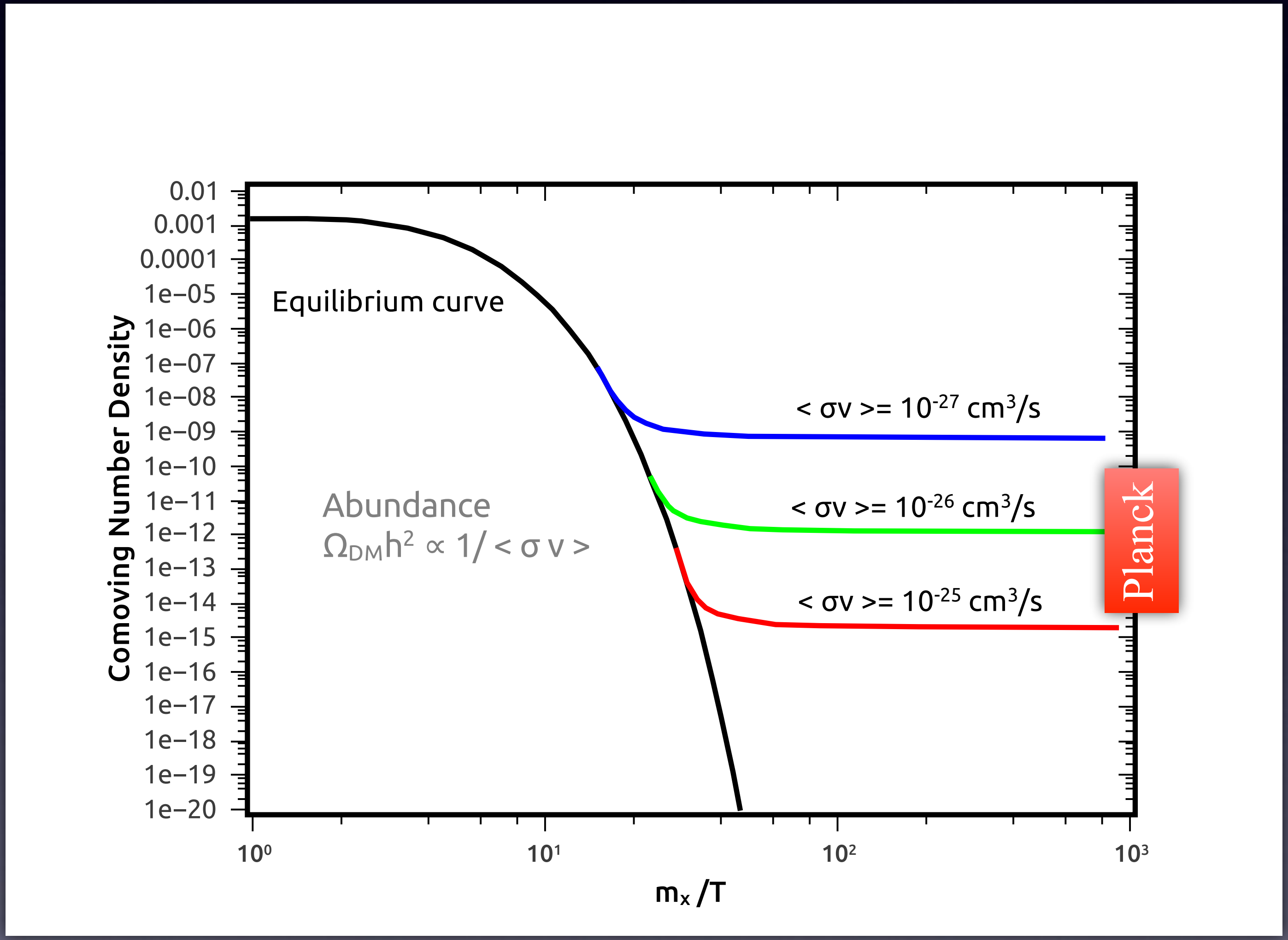

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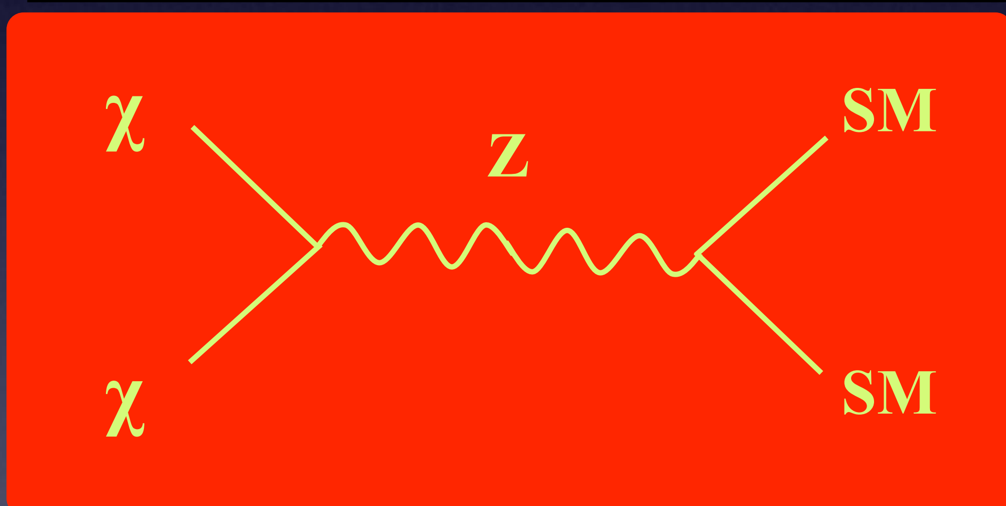
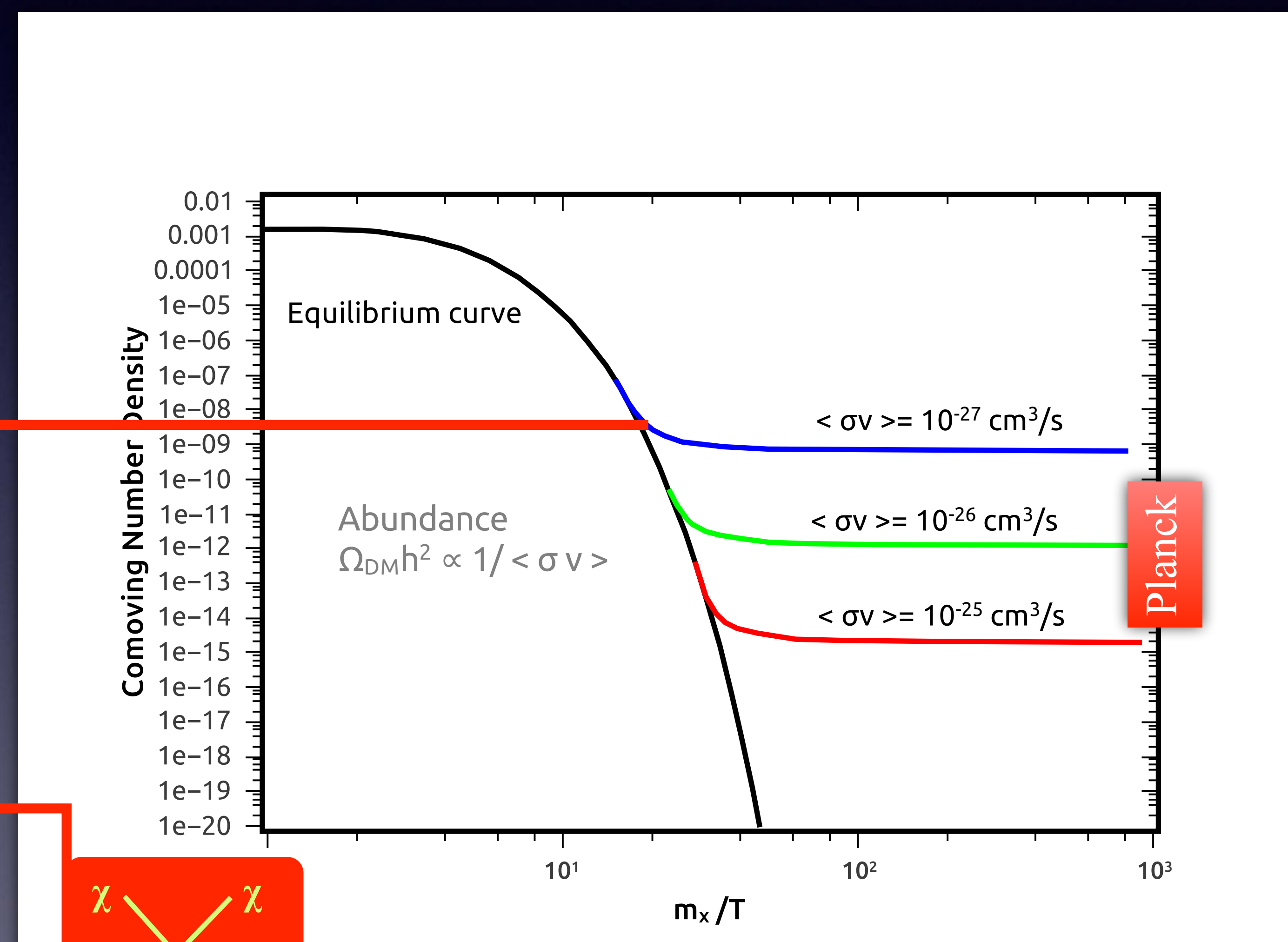
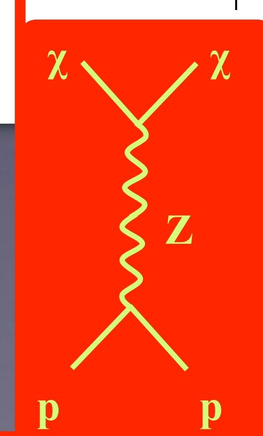
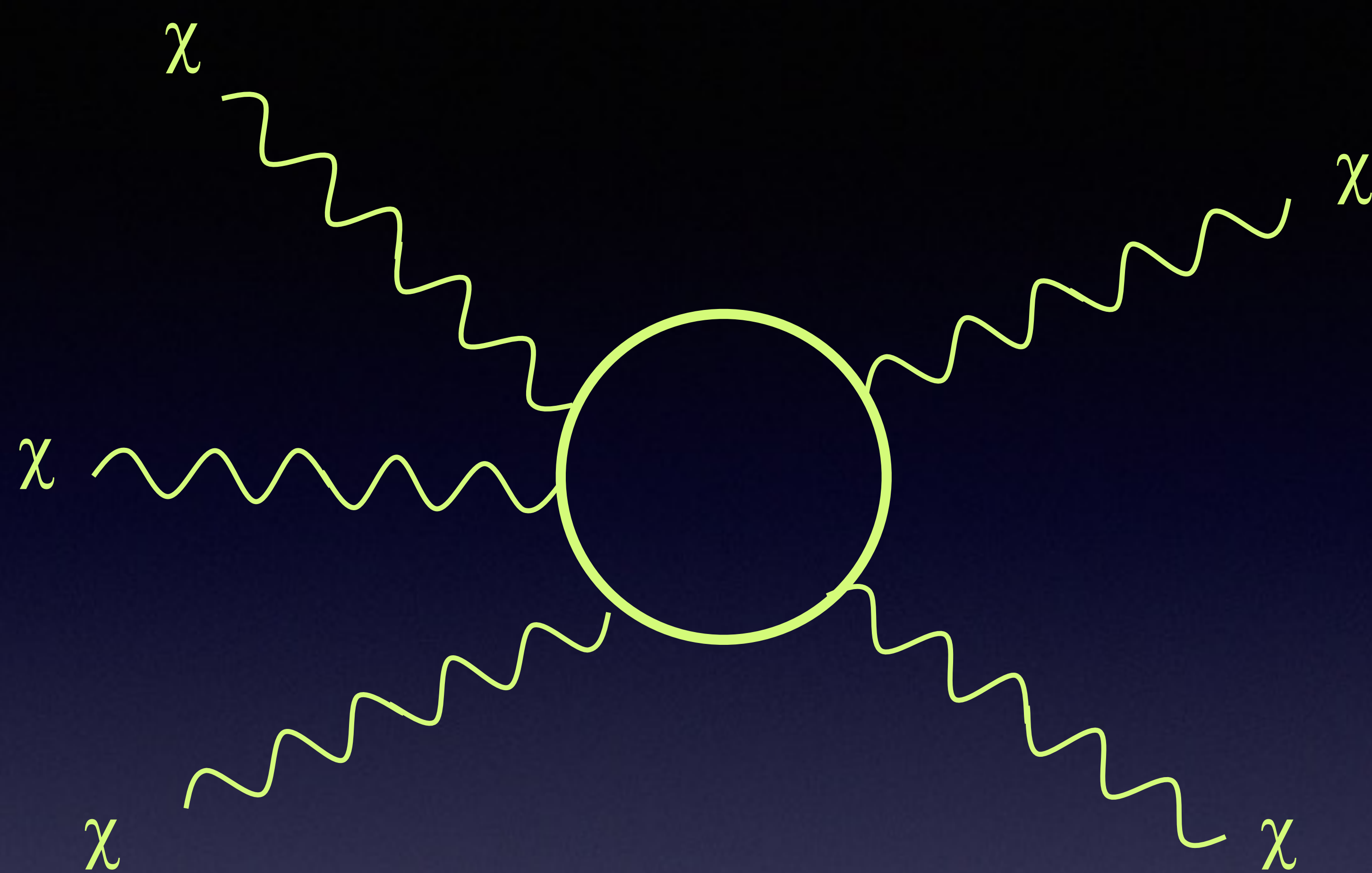




One needs a phase of depletion of dark matter, annihilating to SM to avoid the overabundance. Can we deplete it without even coupling to the SM, and thus avoiding the direct detection conflict?



Yes, the 3 -> 2 process



The depletion of the dark matter χ is obviously slower (only 1 particle χ disappears per interaction) than the 2 -> 2 process, where 2 candidates disappear at each interaction

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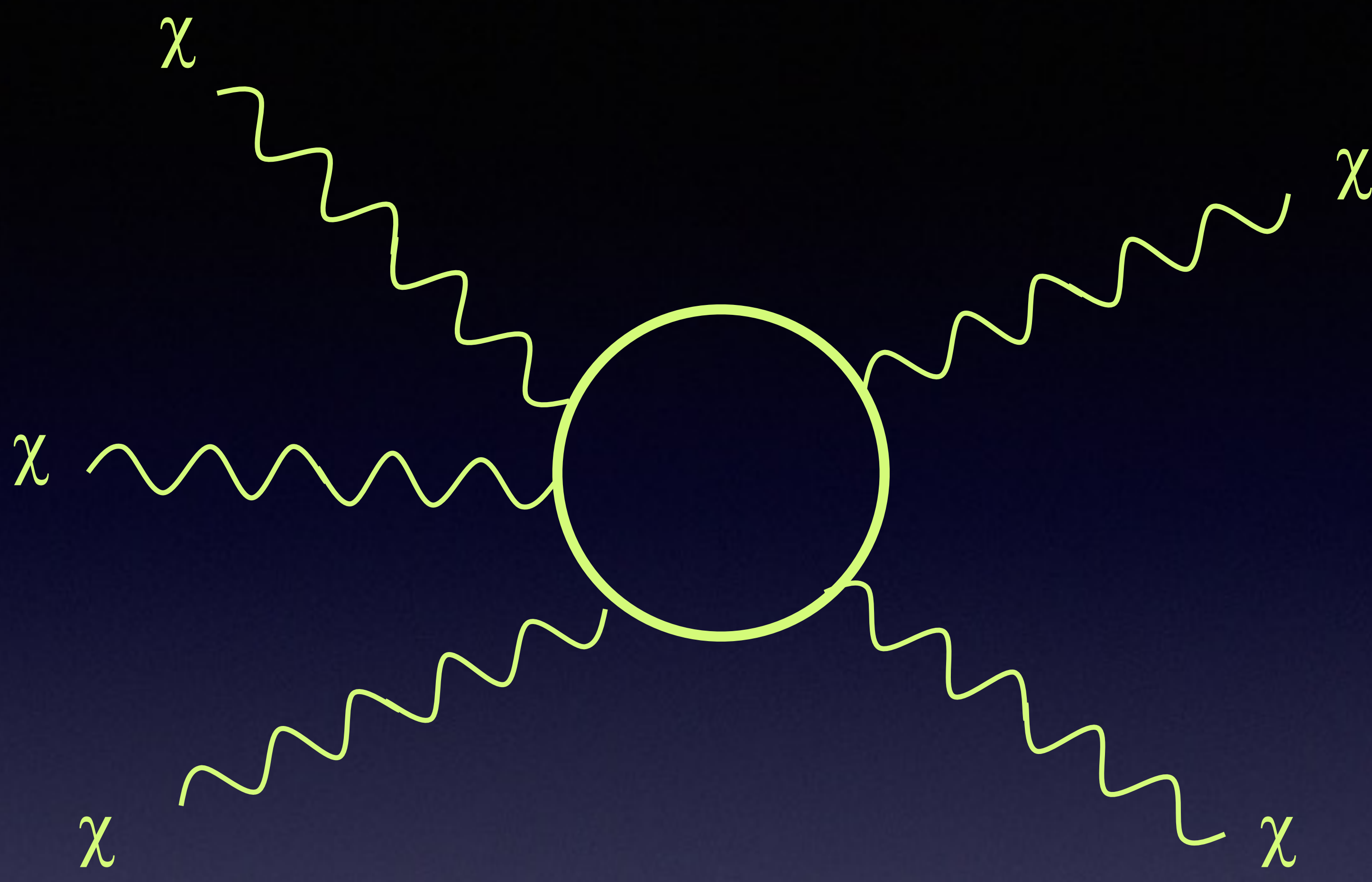

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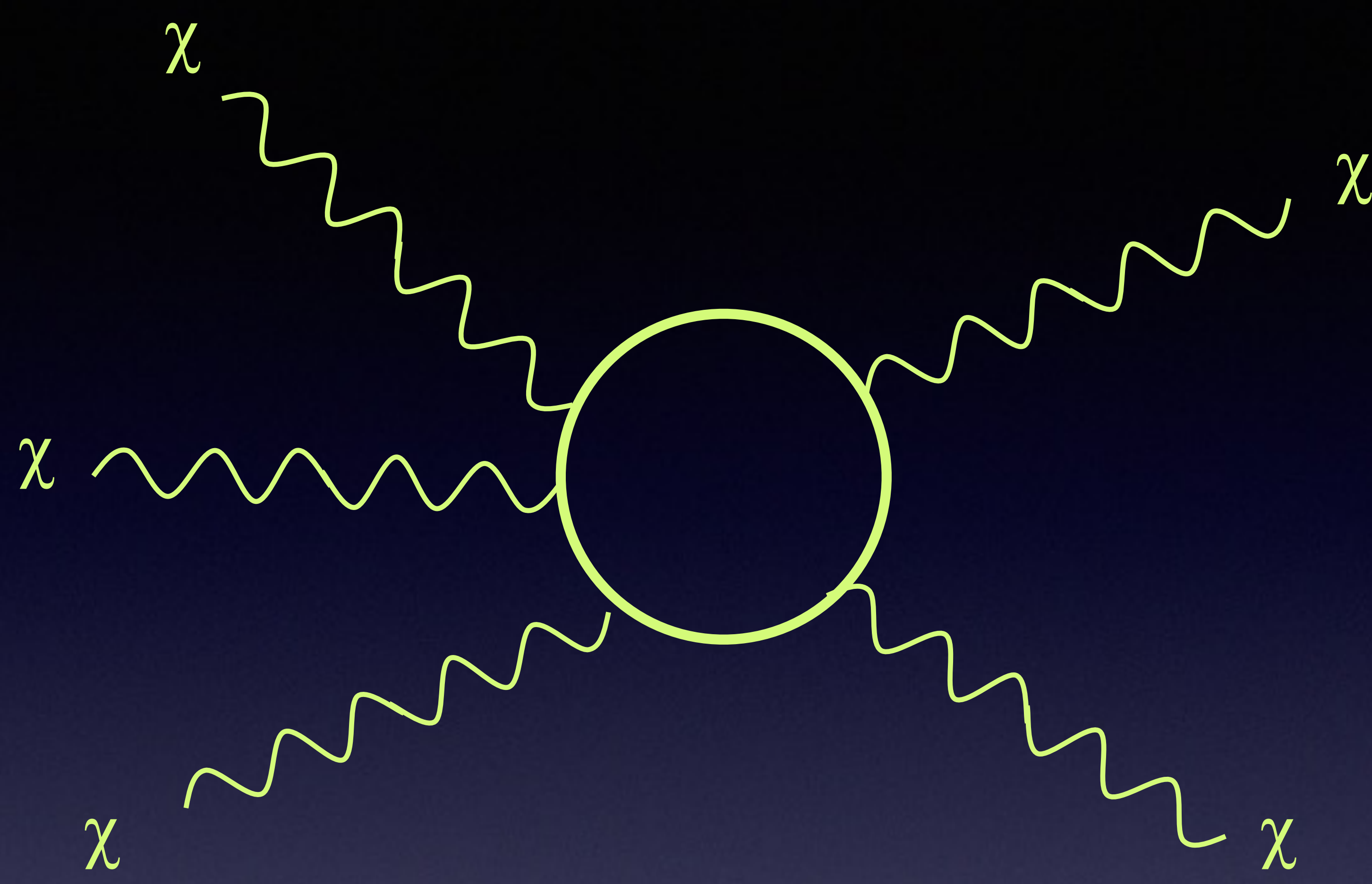

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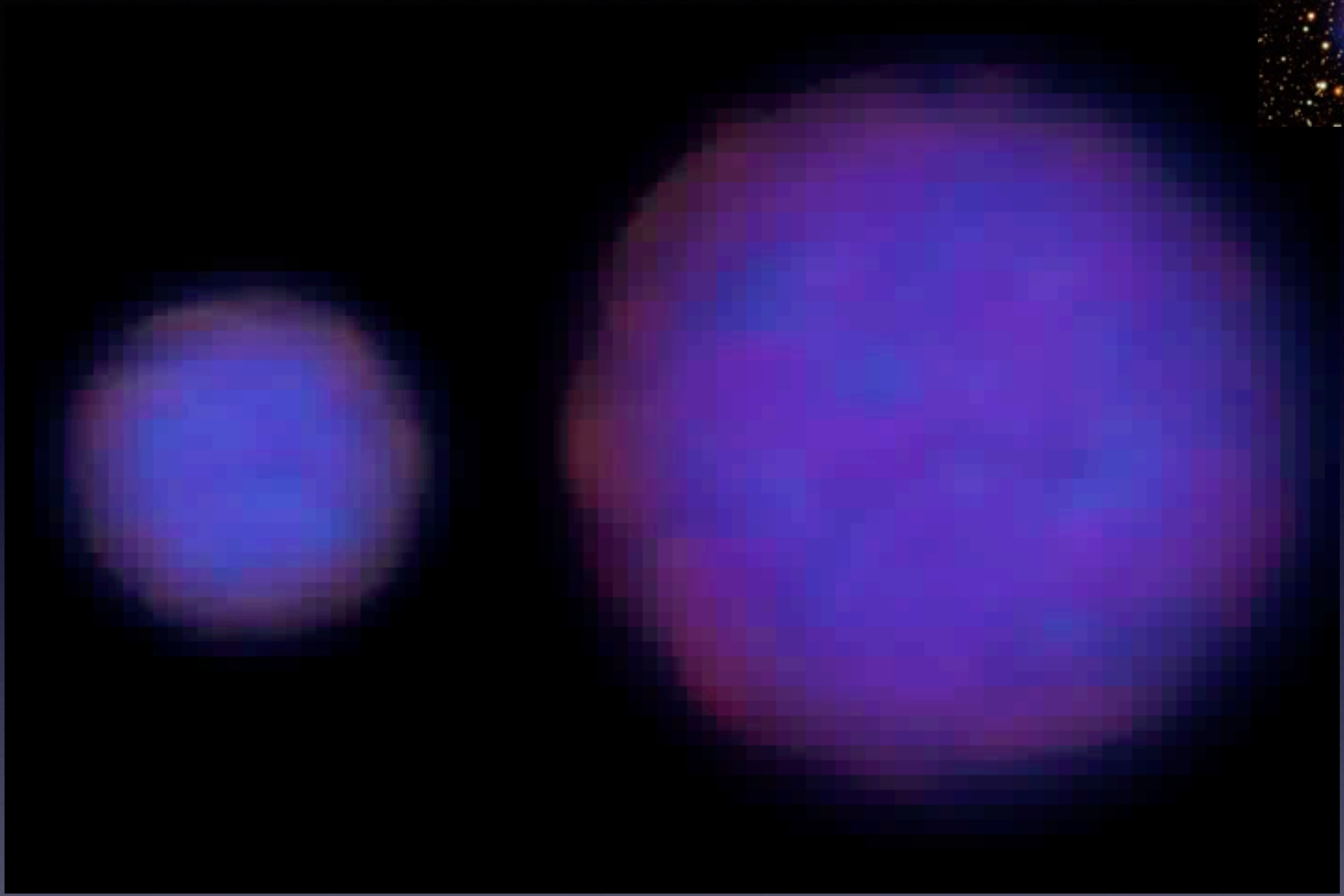
Huge advantage: no need to advocate coupling the the SM: no conflict to direct detection experiments. But strong coupling can be excluded by self interaction

The Bullet Cluster constraint



The Bullet Cluster (1E 0657-558) consists of two colliding clusters of galaxies. Strictly speaking, the name Bullet Cluster refers to the smaller subcluster, moving away from the larger one. It is at a co-moving radial distance of 1.141 Gpc (3.7 billion light-years) and contains around 40 galaxies. They move at around 4500 km/s.

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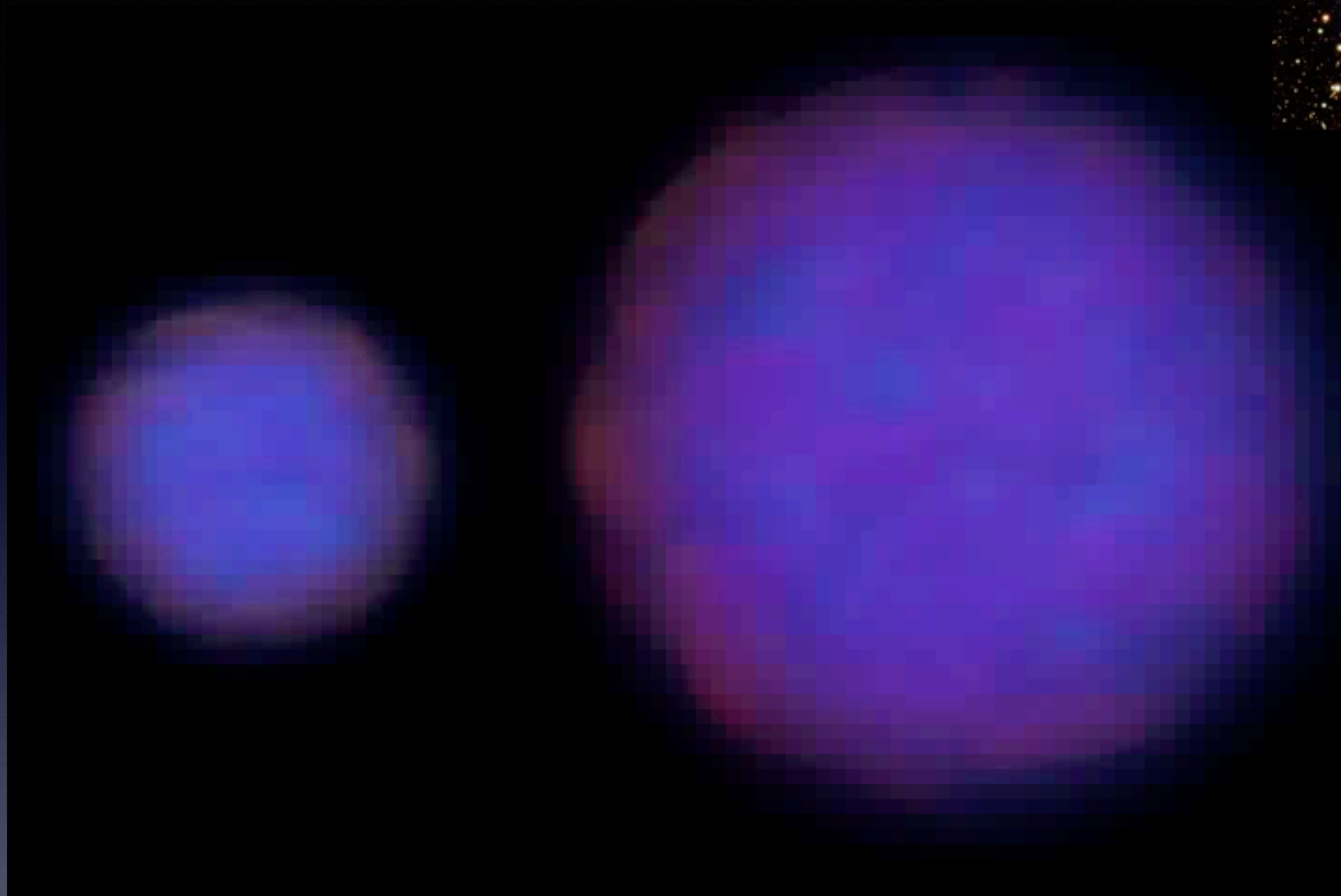

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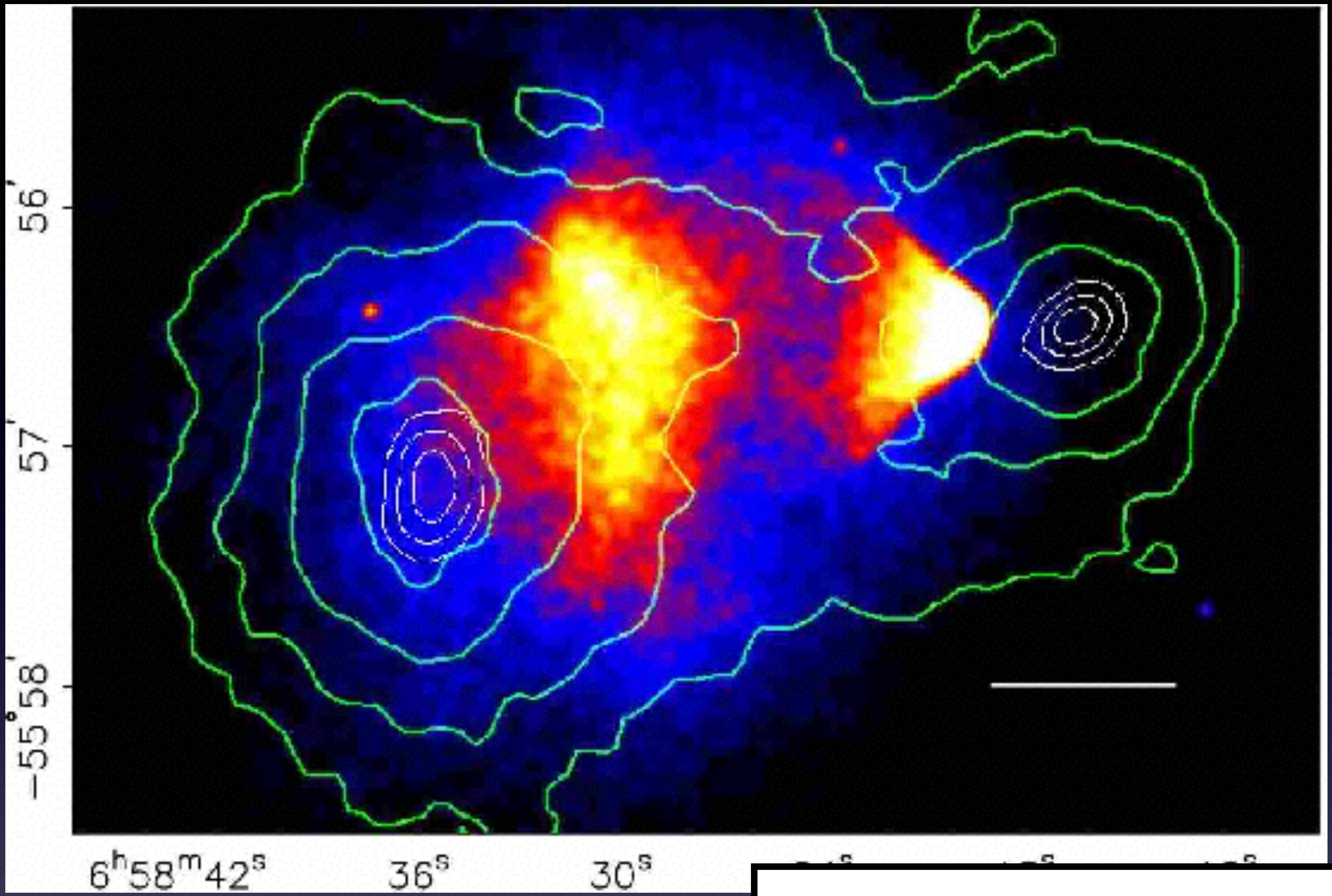
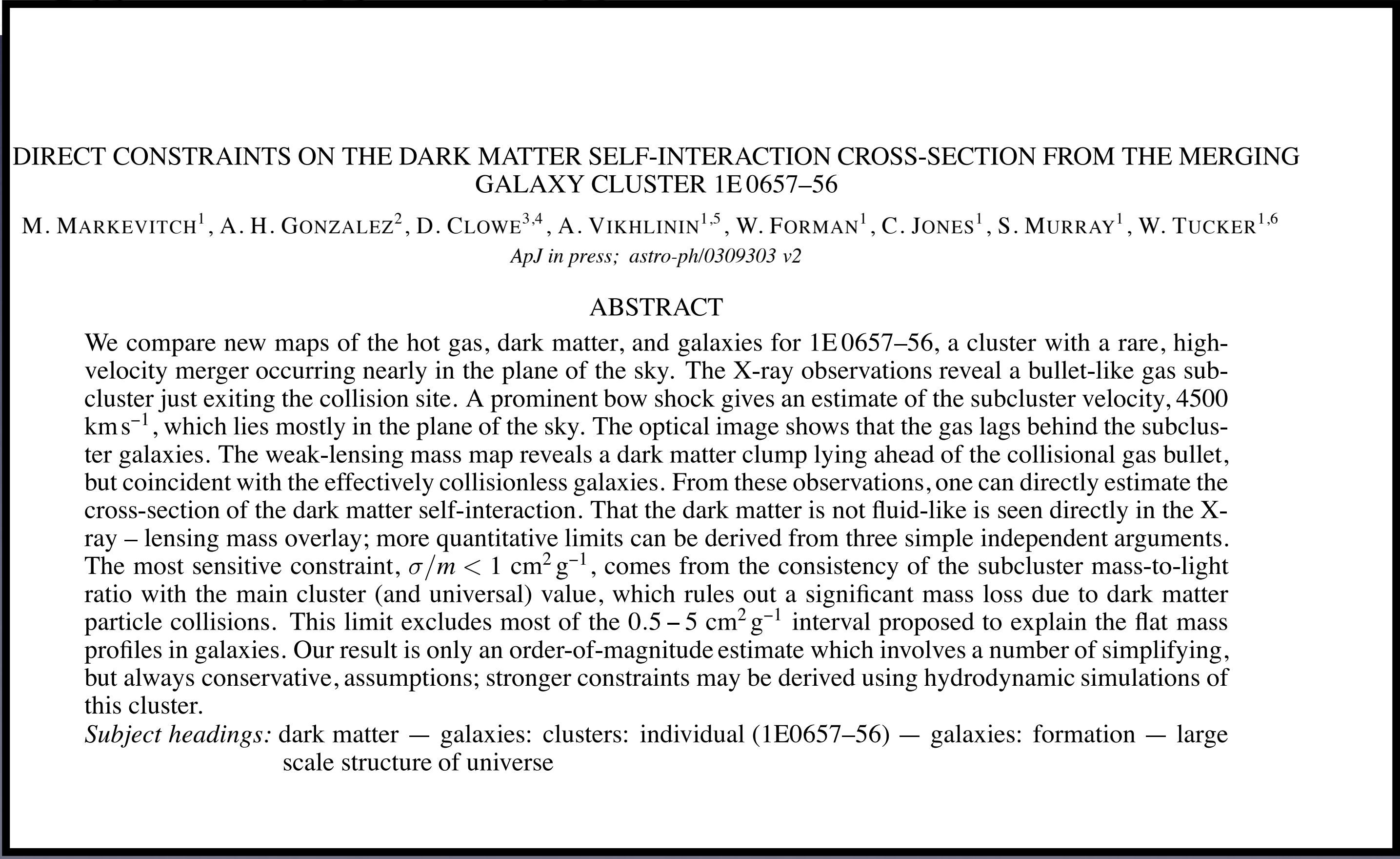


$$\frac{\sigma}{m} \lesssim 1 \text{ cm}^2/\text{g}$$

Markevitch *et al.* [astro-ph/0309303] obtained an *upper limit* because the clusters have NOT interacted

$$1 \text{ cm}^2/\text{g} = 1.8 \times 10^{12} \text{pb/GeV} = 4.62 \times 10^3 \text{GeV}^{-3}$$



DIRECT CONSTRAINTS ON THE DARK MATTER SELF-INTERACTION CROSS-SECTION FROM THE MERGING GALAXY CLUSTER 1E 0657–56

M. MARKEVITCH[1], A. H. GONZALEZ[2], D. CLOWE[3,4], A. VIKHLININ[1,5], W. FORMAN[1], C. JONES[1], S. MURRAY[1], W. TUCKER[1,6]

ApJ in press; astro-ph/0309303 v2

ABSTRACT

We compare new maps of the hot gas, dark matter, and galaxies for 1E 0657–56, a cluster with a rare, high-velocity merger occurring nearly in the plane of the sky. The X-ray observations reveal a bullet-like gas subcluster just exiting the collision site. A prominent bow shock gives an estimate of the subcluster velocity, 4500 km s^{-1}, which lies mostly in the plane of the sky. The optical image shows that the gas lags behind the subcluster galaxies. The weak-lensing mass map reveals a dark matter clump lying ahead of the collisional gas bullet, but coincident with the effectively collisionless galaxies. From these observations, one can directly estimate the cross-section of the dark matter self-interaction. That the dark matter is not fluid-like is seen directly in the X-ray – lensing mass overlay; more quantitative limits can be derived from three simple independent arguments. The most sensitive constraint, $\sigma/m < 1$ cm^2 g^{-1}, comes from the consistency of the subcluster mass-to-light ratio with the main cluster (and universal) value, which rules out a significant mass loss due to dark matter particle collisions. This limit excludes most of the 0.5 – 5 cm^2 g^{-1} interval proposed to explain the flat mass profiles in galaxies. Our result is only an order-of-magnitude estimate which involves a number of simplifying, but always conservative, assumptions; stronger constraints may be derived using hydrodynamic simulations of this cluster.

Subject headings: dark matter — galaxies: clusters: individual (1E0657–56) — galaxies: formation — large scale structure of universe

A Non-abelian Vectorial Dark Matter (VSIMP) respects naturally all these properties

$$\mathcal{L} = -\frac{1}{4}\vec{X}_{\mu\nu}\cdot\vec{X}^{\mu\nu} \qquad \vec{X}_{\mu\nu} = \partial_\mu\vec{X}_\nu - \partial_\nu\vec{X}_\mu + g_X(\vec{X}_\mu\times\vec{X}_\nu)$$

$$\mathcal{L} \supset -\frac{1}{2}g_X(\partial_\mu\vec{X}_\nu - \partial_\nu\vec{X}_\mu)\cdot(\vec{X}^\mu\times\vec{X}^\nu) - \frac{1}{4}g_X^2(\vec{X}_\mu\cdot\vec{X}^\mu)^2$$

S.M. Choi, Y. Hochberg, E. Kufflik, H.M. Lee, Y.M., H. Murayama, Mathias Pierre, « Vector SIMP dark matter » 1705.xxxxx

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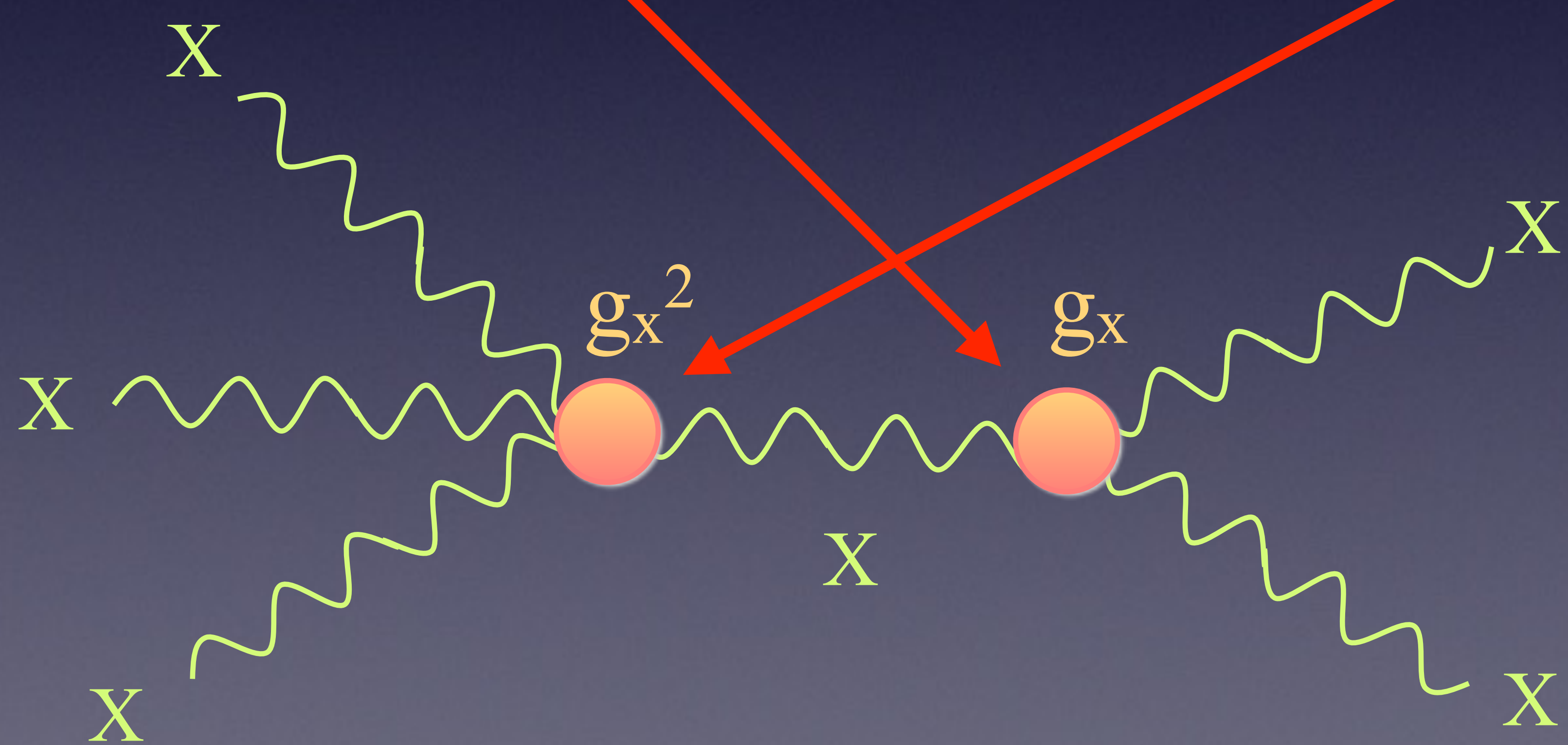

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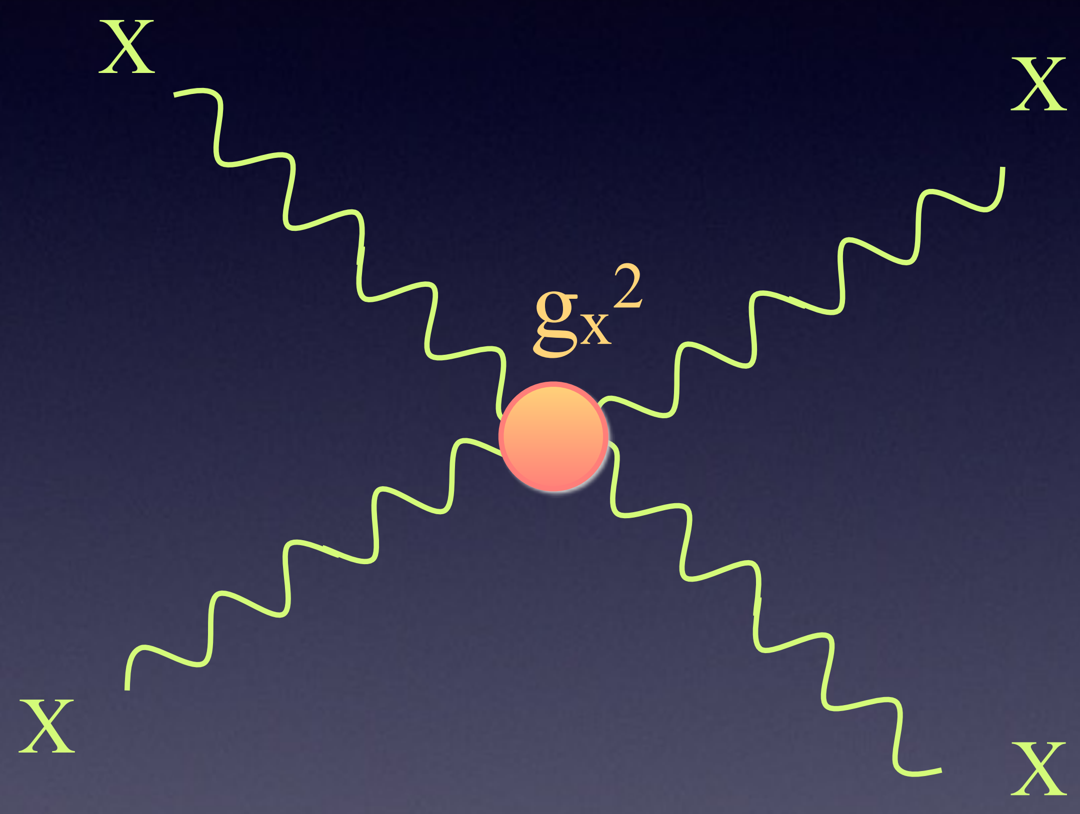
To check self-interaction constraints



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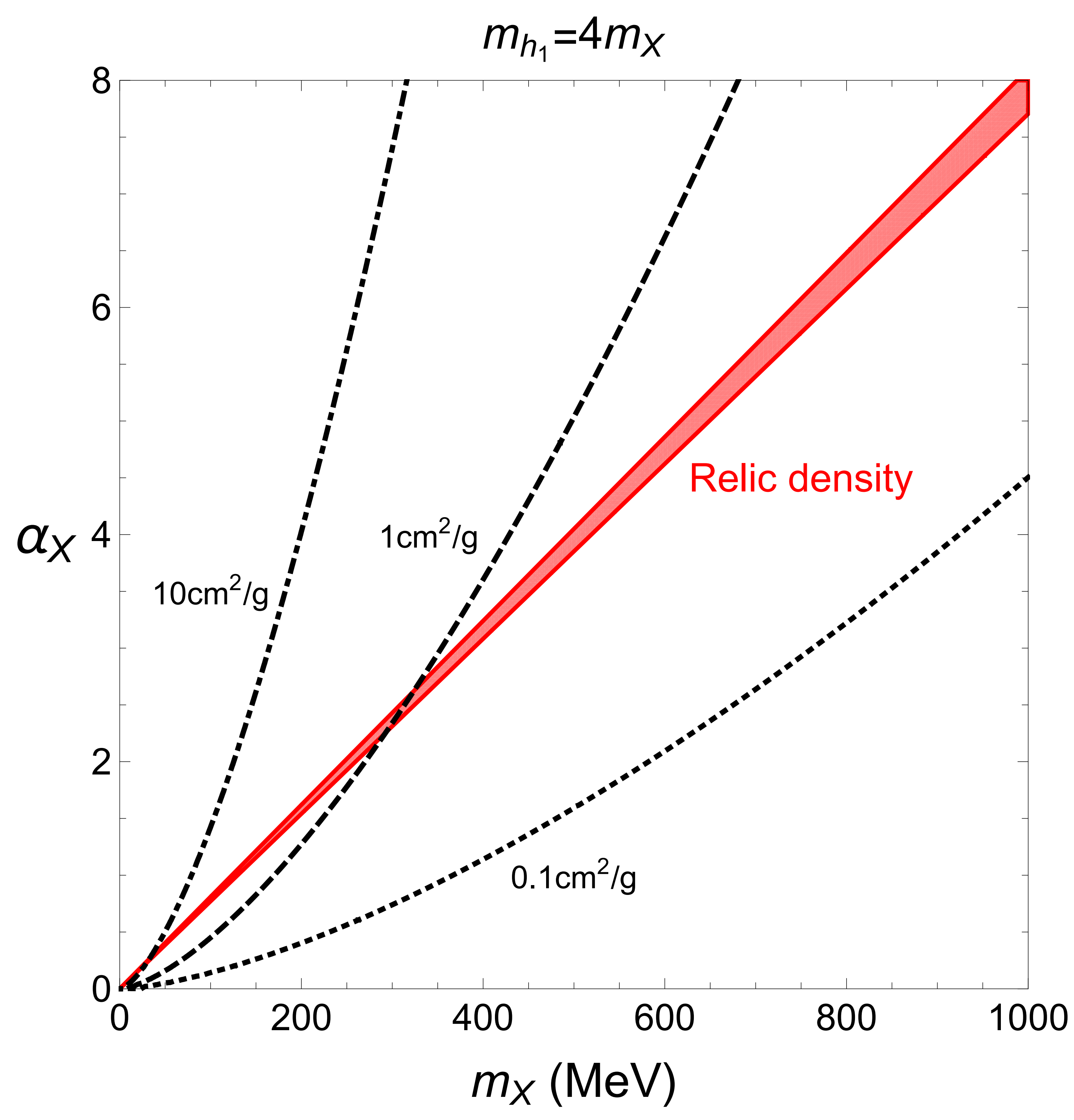

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Unless 3->2 process dominates.

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4) A clear signature through self interaction observations

Beslides

```
H^2 = \left( \frac{\dot a}{a} \right)^2 = \frac{8 \pi G}{3} \rho_{rad}(T) = \frac{8 \pi G}{3} \frac{\pi^2}{15} T^4
\\
aT = \mathrm{cste} ~~~~ \Rightarrow ~~~~ \frac{da}{a} = - \frac{dT}{T}
\\
\frac{dT}{T^3}= -\sqrt{\frac{8 \pi^3 G}{45}} dt ~~~~\Rightarrow ~~~~ t = \frac{M_{PL}}{T^2}\sqrt{\frac{45}{32
\pi^3}} \simeq 0.2 \frac{M_{PL}}{T^2}
\\
t \simeq 3 \times 10^{27}~\mathrm{GeV^{-1}} \sim 200 ~\mathrm{seconds}
\\
n(t_D) \sigma v ~ t_D \simeq 1 ~~~~\Rightarrow n(t_D) \simeq \frac{1}{\sigma v t_D}
\\
v = \sqrt{\frac{3 T_D}{m_p}}\times c \simeq 5 \times 10^8 ~\mathrm{cm ~s^{-1}}
\\
T^{now} = \left(\frac{\rho_m^{now}}{\rho_m(10^9~\mathrm{K})}\right)^{1/3} 10^9~\mathrm{K} = \left( \frac{10^{-30}}
{1.78 \times 10^{-6}~\mathrm{g/cm^3}} \right)^{1/3}10^9~\mathrm{K} \simeq 8 ~\mathrm{K}


\psi_\mu \sim i \sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu \psi

H = h e^{i \frac{\theta}{<H>}} ~~\Rightarrow ~~ W_\mu = i \frac{1}{<H>} \partial_\mu \theta

\mathrm{with}~~ m_{3/2} = \frac{<F>}{\sqrt{3}M_{Pl}}

{\cal L} = \frac{i m_{\tilde G}}{8 \sqrt{6}~ m_{3/2} ~ M_{Pl}} {\color{yellow} \bar\psi} ~  [\gamma_\mu, \gamma_\nu]
{\color{red} \tilde G} ~ {\color{green} G_{\mu \nu}}


\Omega_{3/2} h^2 \sim 0.3 \left( \frac{1 ~\mathrm{GeV}}{m_{3/2}} \right) \left( \frac{T_{\mathrm{RH}}}{10^{10}~
\mathrm{GeV}} \right) \sum
\left( \frac{m_{\tilde G}}{100~\mathrm{GeV}} \right)^2


\Omega_{3/2} h^2 = {\color{yellow} \Omega_{3/2}^{scat} h^2 } + {\color{red}\Omega_{3/2}^{decay} h^2} ~~ \propto~~
{\color{yellow} \frac{T_{RH}\sum  m_{\tilde G^2}}{m_{3/2}^2 M_{Pl}}} +{\color{red} \frac{ \sum M^3_{\tilde Q}}
{m^2_{3/2} M_{Pl}} }
```

The equations

```
n_{e^-} + n_{e^+} = n_{\nu} + n_{\bar \nu} = \frac{3}{2} n_{\gamma}

n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}

\frac{\ddot a}{a} = - \frac{4 \pi G}{3}  \rho ~\Rightarrow ~ q(t) = - \frac{1}{H^2} \frac{\ddot a}{a} = \frac{4 \pi
G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c

n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v
\rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}

\frac{dY}{dT} = \frac{T^2}{H(T)} \langle \sigma v \rangle Y^2 ~~\Rightarrow ~~ Y(T_{now}) = \frac{1}{M_{Pl} T_f
\langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }

\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26
\times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1
~~~~~~~~
\Rightarrow \langle \sigma v \rangle > 10^{-9} h^{-2} ~\mathrm{GeV^{-2}}

\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}

\frac{dY_{a}}{dx_s} =\left( \frac{45}{g_* \pi} \right)^{3/2} \frac{1}{4 \pi^2} \frac{M_P}{m_{a}^5}x_s^4 R

{\color{white} \chi^0_1=} {\color{red} c_B \tilde B + c_1 \tilde H_1 + c_2 \tilde H_2} {\color{yellow} + c_W \tilde
W}
```

The equations

Y_{\tilde G} = \frac{n_{\tilde G}}{n_\gamma} \simeq 10^{-8} \left(\frac{m_{3/2}}{1 ~ \mathrm{GeV}} \right)